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A Scalable, Collaborative, Interactive Light-field Display System

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14. ABSTRACT Light-field displays provide a visual sense of presence by producing a full-parallax three-dimensional aerial and virtual image of portrayed subject matter that satisfies multiple depth cues and that can be engaged naturally and intuitively. This paper documents a comprehensive light-field display system, including computation, photonics, and interaction system components, that is flexible and scalable, establishing a basis for application to both large-scale collaborative and portable, mobile product architectures.

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A Scalable, Collaborative, Interactive Light-field Display System

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Short Title: ZScape Motion Display (ZMD)

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Author Keywords

Light-field; holographic displays; 3D display; holographic video, hogel, holography, integral photography, plenoptic, computed photography

1. Introduction

In this paper we present the results of a multi-phase light-field display development effort, culminating in the ZScape® Motion Display ("ZMD™") family of technologies and prototypes. Achieved goals of the effort include:

- Modularity to support multiple display scales, orientations and configurations, up to 6-foot (1.8 meter) diagonal
- Full-parallax, omni-visibility for correct, natural, no-glasses 3D from all viewing positions
- Wide viewing-angle to accommodate many simultaneous users and natural collaboration
- Rapid update-rates, up to real-time interactive
- Physically-accessible imagery to enable direct natural, gestural, touch and peripheral-based interaction
- Compatibility with a wide variety of existing 3D software applications
- Holographic (hologram-like) image fidelity and perceptibility
- Ease of maintenance, self-contained computation

We outline the system design that was developed in this effort, the photonic approaches explored and their relevant constraints, computational requirements and architectures, and applications demonstrated thus far with the prototype systems.

Light-field Displays: Light-field displays comprise a class of three-dimensional visual information presentation devices capable of creating realistic volumetric images of subject matter with all depth-cues, including full (omni-directional) parallax, occlusion, accommodation, and others, over a broad range of viewing positions. Such displays are generally not thought of as immersive (such as virtual reality or other binocular systems requiring the viewer to wear glasses, goggles or other visual peripherals), but rather as exocentrically-viewed devices, offering the ability to naturally collaborate and interact with the images and with other simultaneous viewers.

Methods to produce light-fields: Various approaches can be considered when designing a light-field display. Diffractive holographic based approaches, involving rapid recording, reconstruction, and erasure cycling, and others involving computation of interference patterns with subsequent reconstruction using high-resolution spatial light modulators have been proposed and prototyped.[1-3] Other approaches, based on integral photography ("IP") involving converting high-density pixel information to angularly-variant arrays of collimated light ray bundles also have been demonstrated.[4-6] Both of these approaches make use of the concept of a "hogel" or "holographic element" as the basic optical element of the light-field display. Here we detail the ZScape® Motion Display (ZMD™) light-field display system that couples a hybrid of refractive and light-modulating elements with a novel system design and computational approaches to produce a convincing dynamic volumetric image that enables natural perception, interaction and collaboration.

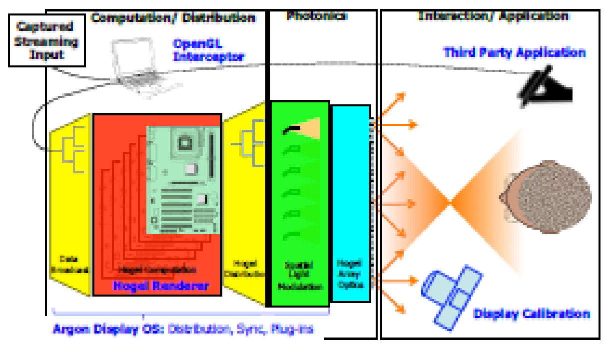

Figure 1: System diagram for a modular light-field system. Software and peripheral modules in blue.

2. System Design

Multiple system modules were considered in the design of ZMD™ (see Figure 1). The Interaction and Application subsystem comprises the area in which the user views and manipulates the light-field image. The Photonics Module, provides the images, comprising spatial light modulator(s)(SLMs) and hogel array optics, where digital information is converted to light in the system. The Computation and Distribution layer feeds the Photonics subsystem, converting abstract 3D representations of data to pixel information, and providing that digital information to (often multiple) spatial light modulators. The Computation system also includes a separate off-the-shelf (OTS) workstation that hosts commercial OTS and proprietary 3D software applications. A proprietary software and firmware-based operating system, called "Argon," integrates all of these physical elements. Argon comprises plug-in modules that govern 3D data interception, data distribution and synchronization, hogel information rendering, and display calibration.

3. ZMD™ Light-field Photonics Approaches

Photonics Design: To produce volumetric imagery for this work, we chose to use a modified IP-based approach to light-field generation that converts pixel information to quasi-collimated, angularly distributed light beam arrays. In this approach, a fixed relationship exists between pixel density, hogel optic size, and hogel-optic numerical aperture, determining the viewing angle, resolution, and nominal depth budget of the display (detailed in Figure 2). In addition, because SLMs are required with pixel sizes less than 50 microns and large physical areas (greater than 15 cm diagonal), multiple SLM projectors must be tiled. Several tiling, relay, SLM and optical approaches were considered in this research, and two particularly successful systems are documented here.

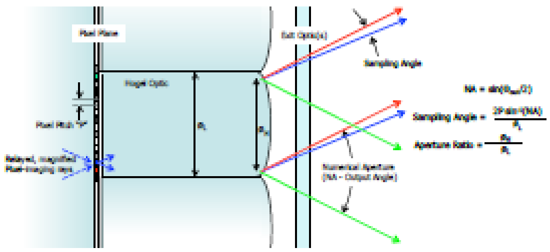

Figure 2: Key basic IP-based light-field hogel optic variables and their interrelationships

Approach 1: OLED + Fiber Tapers: This approach integrates fiber tapers to magnify and abut the output from multiple neighboring organic light-emitting diode (OLED) micro-displays, producing a bed of pixels with uniform emission numerical aperture (NA) and telecentricity.[7] The OLED micro-displays are monochromatic with resolution of 800 by 600 pixels and a relayed pixel spacing of approximately 31 microns, determined by 2X fiber taper-based magnification. We used 3mm-diameter glass doublet lenslets as a refractive component of the hogel optic array, with inter-lenset absorbing grid to mitigate crosstalk. A novel mechanical structure was designed to support the OLED displays, and fiber tapers in groups of six, and allow for minimal seam widths between neighboring tiles (see Figure 3, left).

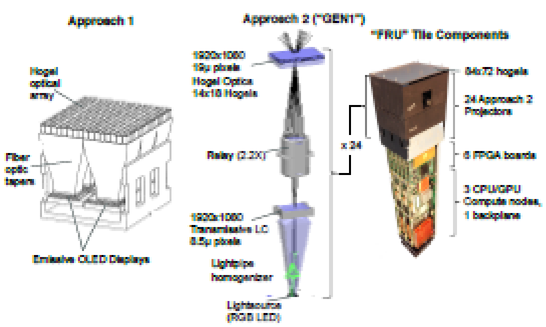

Figure 3: Two of the photonics approaches developed and demonstrated in present research.

Approach 2: LC + Free-space Optical Relay: Transmissive liquid crystal (LC) panels and less-expensive, lighter-weight polymer doublet magnifying relays have been incorporated in another approach, dubbed "GEN1" (see Figure 3, center and right). GEN1 monochrome LC panels with resolution 1920 by 1080 and pixel size of 8.5 microns magnified and relayed to pixels approximately 19 microns in size. A reduction in cost and increase in lifetime (due to replacement of the OLED panels with long-life LC) compared to Approach 1 also incurs reduced telecentricity and some vignetting and luminance non-uniformity due to variable retardation across LC panels and relay NA. Additionally, a light-source and homogenizer are also integrated, increasing the physical length of the system. Color is achieved through separation temporal multiplexing at 120 Hz with RGB LED light sources, resulting in a color frame rate of 40 Hz in this design. Each tile unit comprises 24 LC-based modules, presenting some challenge to achieving color and brightness uniformity and contributing to some artifacts in the resulting light-field image.

Tiling Approach to Scaling: ZMD™ has been designed with a tiled approach to scaling, to enable various sizes of displays to be produced with common components and a simple and robust mechanical assembly (see Figure 4). The GEN1 prototype display, based on photonics Approach 2, consists of 9 tiles, each providing 50 megapixels and 84 by 72 1.6 mm diameter hogels, in a 54 cm diagonal assembly. The tile (schematically shown in Figure 4 - left) represents the basic field-replaceable unit ("FRU") of the GEN1 display system. Arbitrarily-sized displays can be assembled with multiple tiles, each of which attaches to a communications backplane within the mechanical support chassis.

Figure 4: Self-contained tiles assemble modularly to create a single ZMD™. Multiple 9-tile, 54-cm diagonal prototypes have been constructed and are in operation.

4. Computation and Software Architecture

The GEN1 ZMD™ system architecture integrates a sophisticated operating system, called "Argon," for host application data extraction, internal data distribution to render nodes, light-field hogel-view rendering, data distribution and synchronization to SLM buffers, display calibration and interaction device interface.

Scene Description Interception and Rendering: Graphical 3D information, in the form of OpenGL scene descriptions, is intercepted from the computer hosting the software application, and transmitted via Ethernet link to the ZMD™ device in real-time. Within the ZMD™, scene information is buffered to all of the graphical processing units (GPUs) in the render engine. The GPUs render each hogel view with a "double-frustum" model camera, using an OpenGL-based rendering algorithm. The rendering is performed, in essence, from the modeled display emission surface perspective, and thus produces hogel views in a single step process, eliminating the need for costly and memory-intensive block-transform post-processing steps (see Figure 5).[8,9] Multiple alternatives for hogel rendering have been tested, with the best speed/quality-balanced results to-date produced with scan-line based approaches. In the 9-tile GEN1 display pictured in Figure 4, each hogel view image consists of 76 by 76 pixels, spanning 90 by 90 degrees of light-field output per hogel, and each GPU in the system is responsible for generating 2016 independent hogel views.

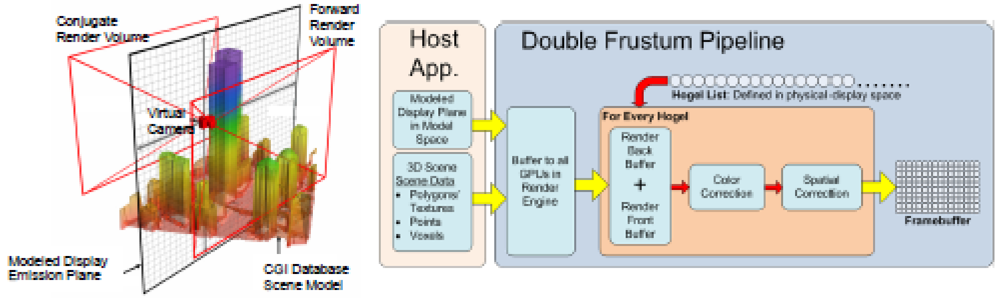

Figure 5: Principle of double-frustum rendering used for parallel generation of light-field data.

System Computational Architecture: Argon has been designed for maximum flexibility, accommodative for scaling the physical display and the number of rendering nodes, alternative types of rendering algorithms, multiple forms of spatial light modulation, and methods of display calibration. Figure 6 details Argon functions.

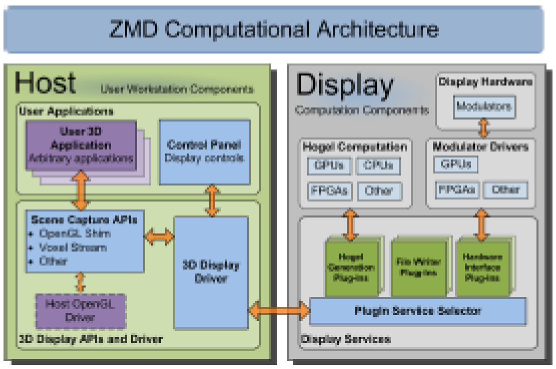

Figure 6: Functional schematic of the ZMD Argon computational operating system

The Argon scene-description interceptor captures the 3D scene drawn by the host application in real-time and replicates the scene information across the array of render nodes within the display over standard Ethernet. In this manner, the ZMD™ can be updated as the scene is modified and manipulated by the host application. Real-time interaction with the light-field scene can be accomplished by registering a 3D I/O device to the ZMD display space. Interactions with the virtual 3D space are still managed by the host application. Thus, any I/O device that is compatible with the host software application and the host computer may be seamlessly integrated with the display (see Figure 7).

Figure 7: Multiple interaction peripherals have been integrated with ZMD, including A: trackball, and B: a 6 degree-of-freedom optically-tracked stylus.

5. Results and Measurements

An early prototype based on photonics Approach 1, is pictured in Figure 8(L). Here, 150 monochrome OLED panels are tiled together to produce a 35cm diagonal display with a 90 degree field of view. The horizontally-oriented prototype enables omni-directional viewing from 360 degrees. The interactive image update rate for this system was demonstrated at approximately 5 Hz, utilizing 2005-vintage OTS Apple MacMini (Intel) CPUs and graphics processing hardware. Pre-generated movie sequences display at frame-rates of over 15 Hz on the system

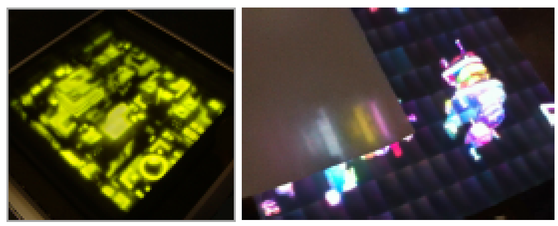

Figure 8: (L) Monochrome, OLED-based prototype based on Approach 1 photonics and off-shelf computation, (R) An aerial image is demonstrated by moving a sheet of paper above the ZMD™ GEN1 prototype.

The 9-tile ZMD™ GEN1 prototype, pictured in Figures 4, 7 and 8(R), was measured for performance over a number of key specifications. Results of these measurements are summarized in Table 1. The GEN1 design features modified reference design CPU/GPU computation engines and field-programmable gate array (FPGA)- based post-processing and hogel data distribution.

Table 1: ZMD™ GEN1 9-tile prototype specifications

Lateral Image Size	354mm X 413mm, 0.54m diag.
Viewing Range	360°; viewable from 4-sides
Brightness	~200 cd/m²
Contrast	70:1
Color	full color, over 4,000 colors
Uniformity	65%
Image Depth	±135mm
Nominal image resolution	2.5mm points (average)
Resolvable image elements	1,800/cm²
Output Range (from normal)	±45°
Form factor	Horizontal orientation (table)
Image Update Rate	>4 Hz (pre-computed)
Refresh Rate	16 Hz (simple content), 3Hz average
Interactive Response Time	<0.1 sec
Active Hogel Yield	>99%
Weight	150 kg
Power consumption	2.5kW

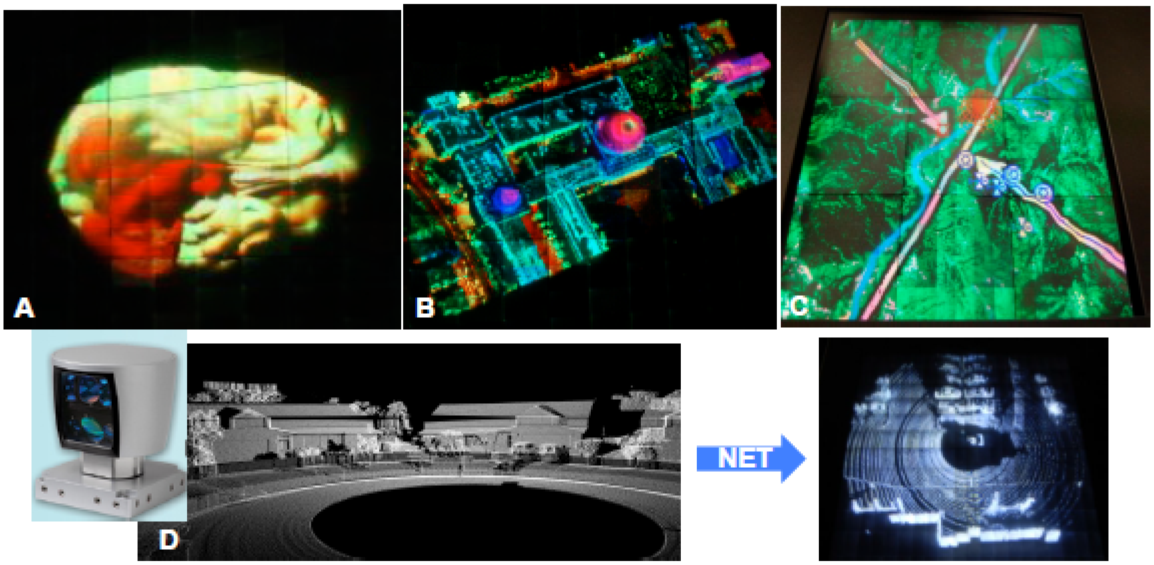

Figure 10: Light-field imagery and applications produced using the ZMD 9-Tile System. A: Medical imagery for training application, B: LIDAR imagery of MIT main buildings, C: Mission planning integrating LIDAR, photography, and CGI symbology, D: Real-time telepresence demonstration with 15Hz. scanning LIDAR system, network transmission, and display on the 9-Tile System at 5Hz update rates.

6. Discussion and Conclusion

A flexible, scalable, interactive light-field display system has been demonstrated with multiple implementations. The system has been integrated for research in a number of application areas, and with a number of usage paradigms. Future work will focus on improvement of optical and SLM quality, scaling and optimization for other use-modalities such as mobile and single-user, integration of alternative approaches for light-field rendering and hogel data distribution architectures, and incorporation of emerging alternative interaction and real-time data capture peripheral systems.

7. Impact of This Research

The development has resulted in a successful baseline light-field system design and multiple reductions to practice for practical light-field display that can be readily scaled, directly-integrated, and performance-optimized for particular applications and configurations. The system presented provides a complete capability that is unprecedented in the literature. Although other researchers have presented papers on what appear to be similar displays, those displays presented do not appear to be modular or scalable, nor do they appear to have scalable, real-time operating systems that enable real-time manipulation of a large, full-color light-field or direct integration with arbitrary software applications through use of a scene description interceptor module. Finally, unprecedented real-time light-field capture, network transfer, and display has been demonstrated in the context of the present research, offering potential for live "holographic" portrayal of real-world scenes and subject matter.

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